Origin of PSRs with $0.1 < P < 0.3$ s and $5 \times 10^5 < \tau < 10^7$ yr after the second Supernova explosion in HMXBs.

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Abstract

The origin of a part of the single pulsars with relatively low magnetic fields $B < 10^{12} G$ and with characteristic times $\tau < 10^7$ yr is established. Such pulsars occur as a result of the disruption of High Mass X-ray Binary Systems after a second Supernova explosion. In these binaries mass accretion onto the surface of X-ray pulsars leads to the decrease of the magnetic field from its initial value $B \sim 10^{12} - 10^{13}$ G down to $B < 10^{12}$ G similar to the processes in Low Mass X-ray Binaries.

KEY WORDS: PULSAR, EVOLUTION, ORIGIN

1   Introduction

As known the first High Mass X-ray Binary (HMXB), Scorpion X-1, was discovered in 1962 (Giacconi et al., 1963). Large number of HMXBs was discovered with rockets before the launch of the first X-ray satellite UHURU in 1971. This is understandable since the angular resolution of the rocket observations being low make the uncertainties in the coordinates of the X-ray sources as high as 5 degrees and massive stars can easily be observed for identification in optic band. After UHURU started to operate many X-ray sources with low fluxes were also discovered. Their origin is considered to be extragalactic. The population of Low Mass X-ray Binaries (LMXBs), their Nova type explosions, and also the light curves of them were predicted (Amnuel et al., 1973; Amnuel et al., 1974) from the data analysis of the sources which were detected by UHURU (Giacconi et al., 1973) and also using the poor data of Nova Cen X-2 (Harriees 1967; Rao et al., 1969) and of Cen X-4 (Evans et al., 1970). Investigations of LMXBs led to very

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important results not only for X-ray astronomy, but also for understanding the population of radio pulsars and the evolution of their magnetic field. Large characteristic times for the magnetic field decay and the alignment of magnetic and rotation axes were understood. Bisnovatyi-Kogan & Komberg (1974 and 1976) showed that accretion of matter in LMXBs must lead to the strong decay of magnetic field of neutron stars. They also predicted the spinning up of the neutron stars in LMXBs and the existence of millisecond radio pulsars (PSRs) with magnetic field B<3×10^{10} G.

During the last ~ 40 years the evolution of single PSRs has been studied on the spin period versus time derivative of the spin period (P-$\dot{\text{P}}$) diagram. Today we may roughly explain the locations of PSRs on different parts of the P-$\dot{\text{P}}$ diagram. However, it is still difficult to understand why a large number of PSRs have periods in the interval 0.1-0.3 sec and magnetic field between 10^{11} G and 10^{12} G. We assert that part of these PSRs may appear after a second Supernova explosion in HMXBs. After the explosion of the massive component, X-ray pulsar must turn into a radio pulsar.

2 Testing the origin of the pulsars with magnetic fields between 10^{11}-10^{12} G and periods between 0.1-0.3 sec.

A P-$\dot{\text{P}}$ diagram is plotted in Figure 1 for the PSRs which have period derivatives between 10^{-13} s/s and 10^{-16} s/s and distances up to 5 kpc. These restrictions were chosen in order to deal only with a sample of single pulsars and to see clearly the regions where the examined PSRs are located. We had to put a limit on distance values since the farther the PSRs are

the larger the errors in their distances are. This was necessary if we also take into consideration that in the recent surveys many distant pulsars were discovered in the plane of the Galaxy in a narrow latitude interval (for the complete data see ATNF Pulsar Catalogue 2003; Guseinov et al., 2002 and the references therein). There is no search with similar sensitivity for most of the parts of the sky.

As it is seen in Figure 1, all the PSRs with ages up to 10^5 years have magnetic fields larger than 10^{12} G. From this figure we can say that PSRs are practically always born with such magnetic field values. All 23 PSRs which have genetic connections with Supernova remnants (Manchester et al., 2001; Guseinov et al., 2003) are located on this part of the P-$\dot{\text{P}}$ diagram. Therefore, without any doubt PSRs are mostly born in this region of the P-$\dot{\text{P}}$ diagram. But this does not mean that right after a Supernova explosion some PSRs can not have several times smaller magnetic field values at birth.

As seen in Figure 1, the number of pulsars which are located in between the constant magnetic field lines $10^{11} - 10^{12}$ G and have ages up to 5×10^5 yr is very small, whereas the number of pulsars having the same magnetic field values with larger ages is high. In contrast we do not see a similar situation in $10^{12} < B < 10^{13} G$ interval. As magnetic fields of single PSRs with ages 5×10^5-10^7 yr practically do not change, their evolutionary tracks must be parallel to the constant magnetic field lines. Therefore, part of the PSRs with $B \simeq 10^{11} - 10^{12} G$ may be born in the region with $P \simeq 0.1 - 0.3 sec$ directly with large value of τ. This may be due to the second Supernova explosion in HMXBs. In this way, after the explosion in the massive binary, X-ray pulsar becomes a radio pulsar. If we compare a pulsar having such origin with a single born pulsar, the former must have several times smaller magnetic field compared to the single born pulsar even though

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both of them have the same initial magnetic field strengths, because there occurs magnetic field decay due to the accretion during the HMXB phase. This process is similar to the one that takes place during disk accretion in LMXBs (Bisnovatyi-Kogan and Komberg 1974; Bisnovatyi-Kogan and Komberg 1976).

Kinematic ages of these PSRs on average must be smaller than the kinematic ages of the single born pulsars with the same values of characteristic times (τ). This is reasonable since the space velocities of the single born pulsars are considerably larger than the center of mass velocity of HMXBs. We should also take into account that the radio pulsar which is born after the second Supernova explosion continues to move with its orbital velocity, but on average the orbital velocities are also smaller than the space velocities of single born PSRs. Therefore, PSRs which appear after the second Supernova explosion may have on the average several times smaller distances from the Galactic plane (|z|).

In order to test this idea we have chosen two groups of PSRs with similar characteristic ages. The number of PSRs in each group is almost the same. In the P-$\dot{\text{P}}$ diagram the boundary of the first group is determined as $0.1 < P < 0.3$ sec, $5 \times 10^5 < \tau < 10^7$ yr and the second group has the boundaries $0.6 < P < 1.3$ sec, $6 \times 10^5 < \tau < 10^7$ yr and $\dot{P} > 3 \times 10^{-15}$ s/s. It is necessary to note that we specially restricted the groups we are working on, so that, the pulsars in the first and the second groups have different bands of evolutionary tracks on the P-$\dot{\text{P}}$ diagram and their number versus age distributions are similar.

For our pulsar samples the |z|-τ diagrams are represented in Figures 2a and 2b. As it is seen, there is no considerable increase in |z| with increasing τ for the first group of PSRs. At a smaller value of τ, |z| increases ap-

proximately with τ, but there is no linear proportionality similar to the one seen in the second group of PSRs (Figure 2b). As it is seen in Figure 2a, at every value of τ there is a large number of PSRs with small |z| values. Due to their high velocities the part of single born PSRs which are near the Galactic plane must decrease as we go towards higher τ values (see Figure 2b). From Figure 2a we noticed that PSRs in the first group have definitely smaller average |z| values compared to the PSRs of the second group (see Figure 2b). This should be related to the appearance of newborn PSRs in the first group with different values of τ. These PSRs are directly placed in the low-B-large-τ part of the P-$\dot{\mathrm{P}}$ diagram.

For the sake of safety we checked PSRs with $10^7 < \tau < 10^8$ years and saw the same tendency. However, at such ages the changes in the beaming factor and the decrease in the pulsar voltage start to affect the pulsar population creating uncertainties. Naturally, this may have influence on the average value of the deviation from the Galactic plane.

Do the important differences that we saw in Figure 2a and in Figure 2b between the PSRs in the first and in the second groups depend on selection effects? Can it be true that different velocities and average |z| values are due to other parameters of these PSRs being different? Even though this idea has a low probability of occurrence let us investigate other parameters of PSRs in both groups in order not to leave any suspects. Can the locations of the PSRs in the first group with respect to the Sun be responsible for their small |z| values when compared to the |z| values of the PSRs in the second group? In Figure 3a and in Figure 3b the distance from the Sun (d) versus the galactic longitude (l) of these two samples are plotted. From these figures we deduce that PSRs in the second group are a little bit farther away from the Sun than the PSRs in the first group. Thus, the distances

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have no effect on our results.

In general it is known that radio luminosities of PSRs depend very weakly on their locations on the P-$\dot{\text{P}}$ diagram. In Figure 1, the locations of the PSRs in both of the groups slightly, but not significantly, differ. Therefore, PSRs in both groups must have similar fluxes and luminosities. On the other hand, conditions for PSR observation depend on the directions in the Galaxy. This is expected since in different directions of the Galaxy pulsar searches with varying accuracies and sensitivities were performed at different frequencies. Luminosities at 400 MHz versus Galactic longitude are shown in Figure 4a and in Figure 4b whereas luminosities at 1400 MHz versus Galactic longitude are represented in Figure 5a and in Figure 5b for our samples. As seen from these figures there is no difference for both groups in their directions, luminosities and fluxes. Therefore, the differences in the average values of |z| for both groups of PSRs are not related to the selection effects.

3   The difference in space velocities of the pulsars in the groups

Now let us discuss data about the space velocities of some PSRs from both of the groups. Some data for 5 PSRs from the first group and for 12 PSRs from the second group for which proper motions are known are given in Table 1. As the table indicates PSRs from the first group not only have considerably small |z| values but also have small space velocities. The space velocity of each pulsar may roughly be estimated using the proper motion (Harrison et al., 1993; Fomalont et al., 1997; Lyne et al., 1982; Bailes et al., 1990) and distance values (Guseinov et al., 2002). Therefore, we saw that kinematic

characteristics of these two groups of pulsars are actually different.

4   Examination of the X-ray data of the pulsars in both groups

After the Supernova explosion, as the X-ray component in HMXB may directly show itself in the regions where τ values are high, it may have significantly large X-ray luminosity compared to other pulsars with similar characteristic times. Because the time it has spent as a radio pulsar is smaller than the value of its characteristic time.

Lists of PSRs from which X-ray radiation was observed in 0.1-2.4 keV and in 2-10 keV bands were published by Becker and Trumper (1997), Becker and Aschenbach (2002) and Possenti et al., (2002). As seen in these lists, from PSRs J1057-5226, J0358+ 5413, J0538+2817 and J1932+1059 X-ray radiation was detected. All of these PSRs belong to our first group and there is no other pulsar with τ in the interval $5 \times 10^5 - 10^7 yr$ from which X-ray radiation was observed. In the mentioned lists there are yet two PSRs, namely J0826+2637 and J0953+0755, with several times larger characteristic times. Both of these pulsars are directly located in the belt along which PSRs from the first sample evolve. Yet 3 PSRs, namely J1952+3252, J0117+5914 and J1302-6350, which radiate X-rays, are located on the P-$\dot{P}$ diagram right in front of the first sample of pulsars, as they have $10^5 < \tau < 5 \times 10^5$ yr. Only Geminga pulsar which has a magnetic field about 1.7×10^{12} G is located in the boundary of the second sample of PSRs. All other PSRs with larger ages from which X-ray radiation have been observed are old millisecond pulsars. These deductions strongly justify what we have suggested about the origin of a great deal of the PSRs that are born with magnetic fields between

$10^{11} - 10^{12}$ G and characteristic ages between $5 \times 10^5 - 10^7$ years.

5   Conclusions

Part of the PSRs with $10^{11} < B < 10^{12}$ G and with $P < 0.3$ sec appears after the second Supernova explosion in HMXBs. These PSRs, before the second explosion, were X-ray components of HMXBs. As a result of accretion onto these pulsars, there occurs magnetic field decay. These PSRs must conserve their orbital and center-of-mass velocities, the sum of which is on average smaller than the space velocity of single born pulsars. On the other hand, distances of HMXBs from the plane of Galaxy are not large and real ages of the discussed pulsars may be smaller than their characteristic times. Therefore, these PSRs must have small space velocities and their distances from Galactic plane must also be smaller than the single born pulsars with the same values of τ. On the other hand, they must have significantly larger X-ray luminosity than the single born PSRs with similar values of τ. The observational data confirm all these expectations.

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PSR	μ	d	|z|	$\log \tau$
	(mas yr^{-1})	(kyr)	(kyr)	
J0358+5413	13.9 (1)	2	0.028	5.75
J1453-6413	26.9 (2)	1.84	0.142	6.01
J1559-4438	14.0 (1)	1.63	0.181	6.60
J1932+1059	88.1 (3)	0.2	0.013	6.49
J2055+3630	4.2 (4)	4.2	0.409	6.98
J0502+4654	11.3 (4)	1.7	0.091	6.26
J0630-2834	38.1 (1)	1.8	0.519	6.44
J0653+8051	19.0 (4)	2.3	1.038	6.70
J0837+0610	51.0 (3)	0.6	0.266	6.47
J0946+0951	43.4 (3)	0.98	0.670	6.69
J1136+1551	371.3 (3)	0.24	0.224	6.70
J1509+5531	99.8 (3)	1.4	1.108	6.37
J1709-1640	3.0 (1)	0.9	0.212	6.21
J1913-0440	8.6 (4)	3.1	0.384	6.51
J1919+0021	2.2 (4)	2.95	0.316	6.42
J2225+6535	182.4 (4)	2.0	0.238	6.05
J2354+6155	22.8 (4)	3.1	0.010	5.96

Table 1. Name, proper motion, d, |z| and τ values of 5 pulsars from the first sample and of the following 12 pulsars from the second sample. The numbers in parenthesis in the second column indicate the references for the proper motions.

(1) Fomalont et al., (1997); (2) Bailes et al., (1990); (3) Lyne et al., (1982);

(4) Harrison et al., (1993)

Figure Captions

Figure 1: The $P - \dot{P}$ diagram for all pulsars that have distances up to 5 kpc with $10^{-16} < \dot{P} < 10^{-13}$ s/s. Pulsars that form our first sample are shown with '+' sign in the figure. They have $0.1 < P < 0.3$ sec, $5 \times 10^5 < \tau < 10^7$ yr. The second sample that we consider appear with a 'o' sign. These pulsars have $0.6 < P < 1.3$ sec, $\dot{P} > 3 \times 10^{-15}$ s/s, $6 \times 10^5 < \tau < 10^7$ yr.

Figure 2a: $|z|$-τ diagram for the pulsars with $0.1 < P < 0.3$ sec, $5 \times 10^5 < \tau < 10^7$ yr and $d \leq 5$ kpc.

Figure 2b: $|z|$-τ diagram for the pulsars with $0.6 < P < 1.3$ sec, $\dot{P} > 3 \times 10^{-15}$ s/s, $6 \times 10^5 < \tau < 10^7$ yr and $d \leq 5$ kpc.

Figure 3a: The d versus l diagram for the pulsars with $0.1 < P < 0.3$ sec, $5 \times 10^5 < \tau < 10^7$ yr and $d \leq 5$ kpc.

Figure 3b: The d versus l diagram for the pulsars with $0.6 < P < 1.3$ sec, $\dot{P} > 3 \times 10^{-15}$ s/s, $6 \times 10^5 < \tau < 10^7$ yr and $d \leq 5$ kpc.
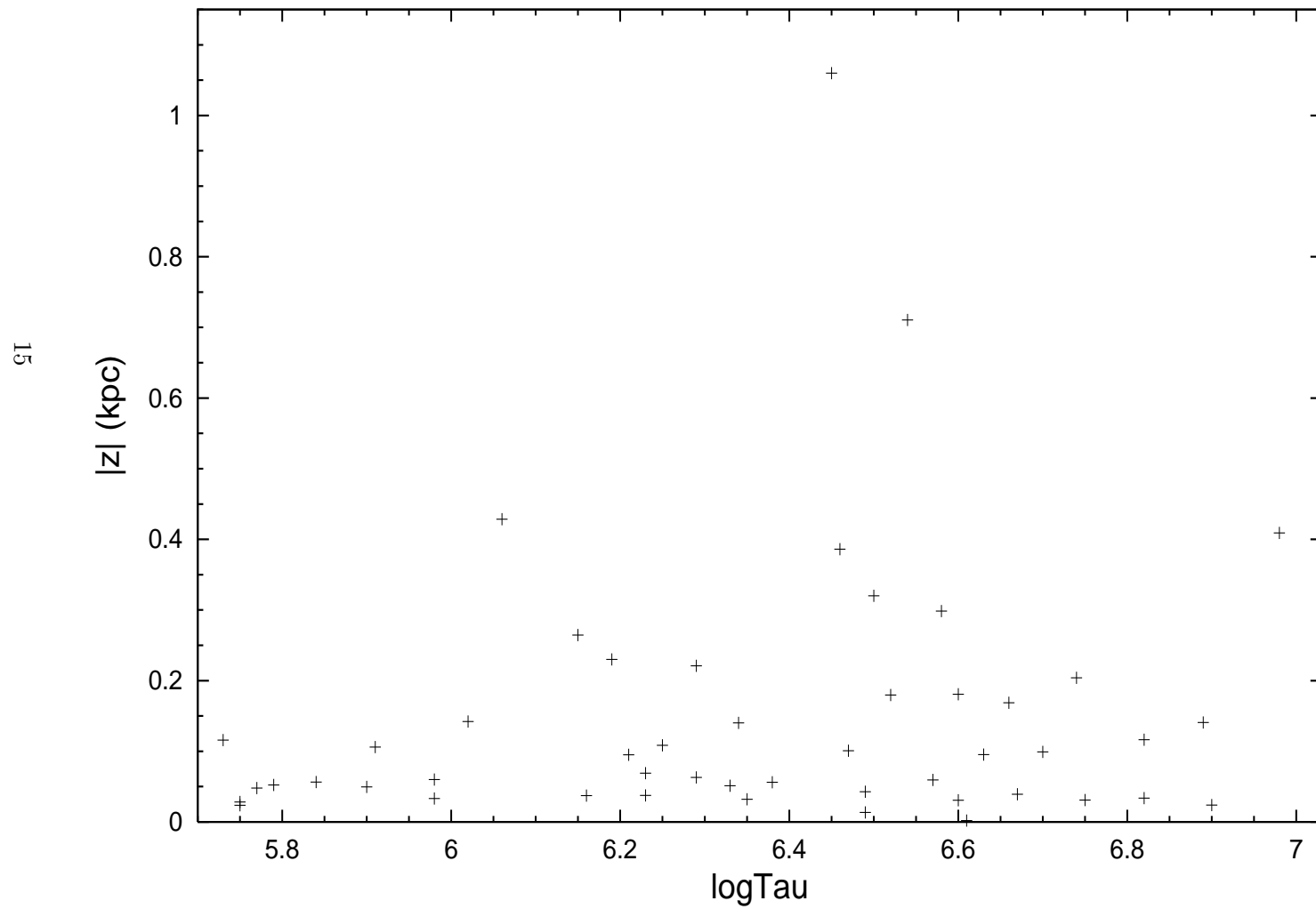
Figure 4a: The luminosity at 400 MHz L_{400} versus l diagram for the pulsars with $0.1 < P < 0.3$ sec, $5 \times 10^5 < \tau < 10^7$ yr and $d \leq 5$ kpc.
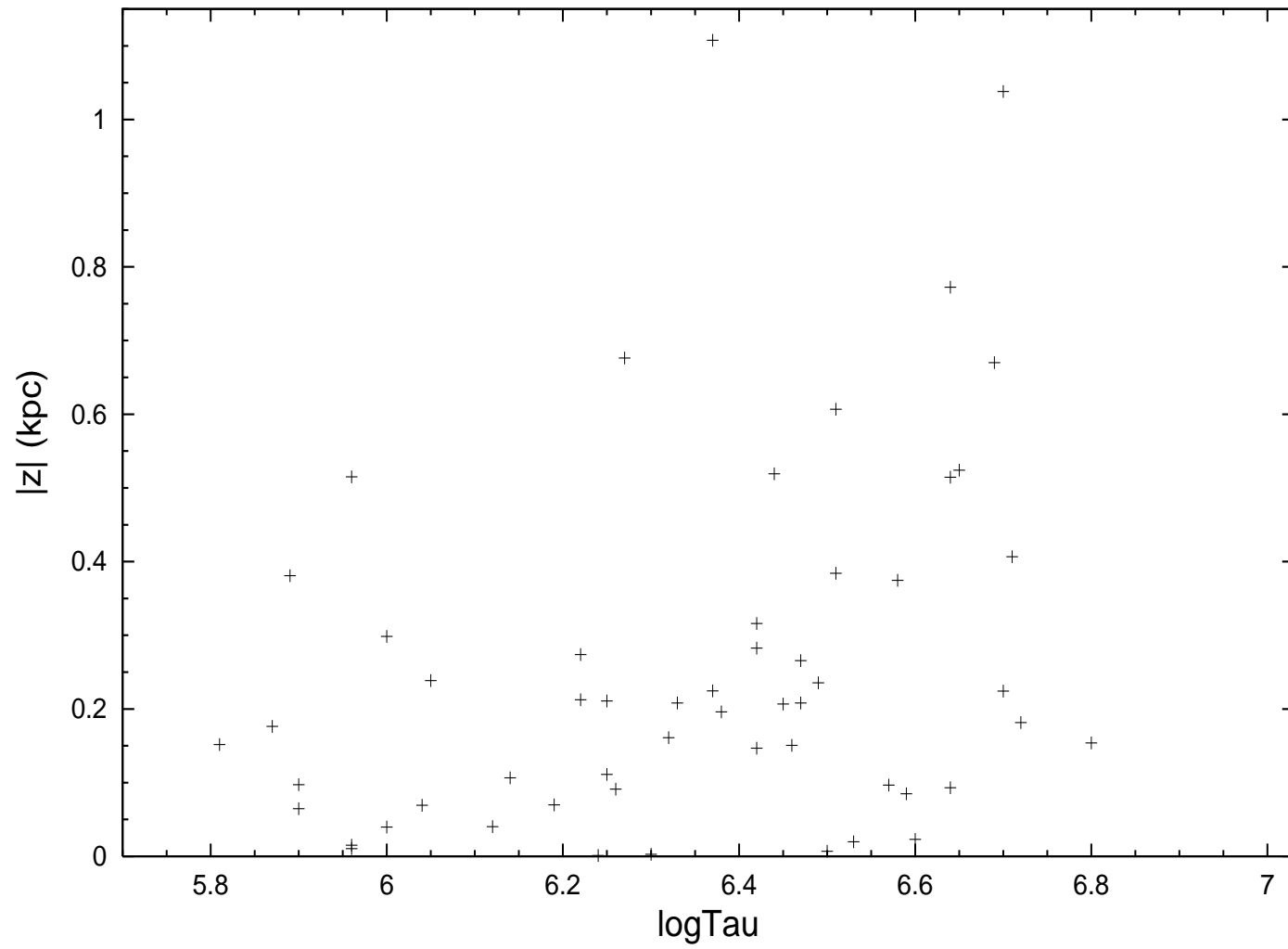
Figure 4b: The luminosity at 400 MHz L_{400} versus l diagram for the pulsars with $0.6 < P < 1.3$ sec, $\dot{P} > 3 \times 10^{-15}$ s/s, $6 \times 10^5 < \tau < 10^7$ yr and $d \leq 5$ kpc.

Figure 5a: The luminosity at 1400 MHz L_{1400} versus the galactic longitude l diagram for the first sample in which the pulsars have $0.1 < P < 0.3$ sec, $5 \times 10^5 < \tau < 10^7$ yr and $d \leq 5$ kpc.

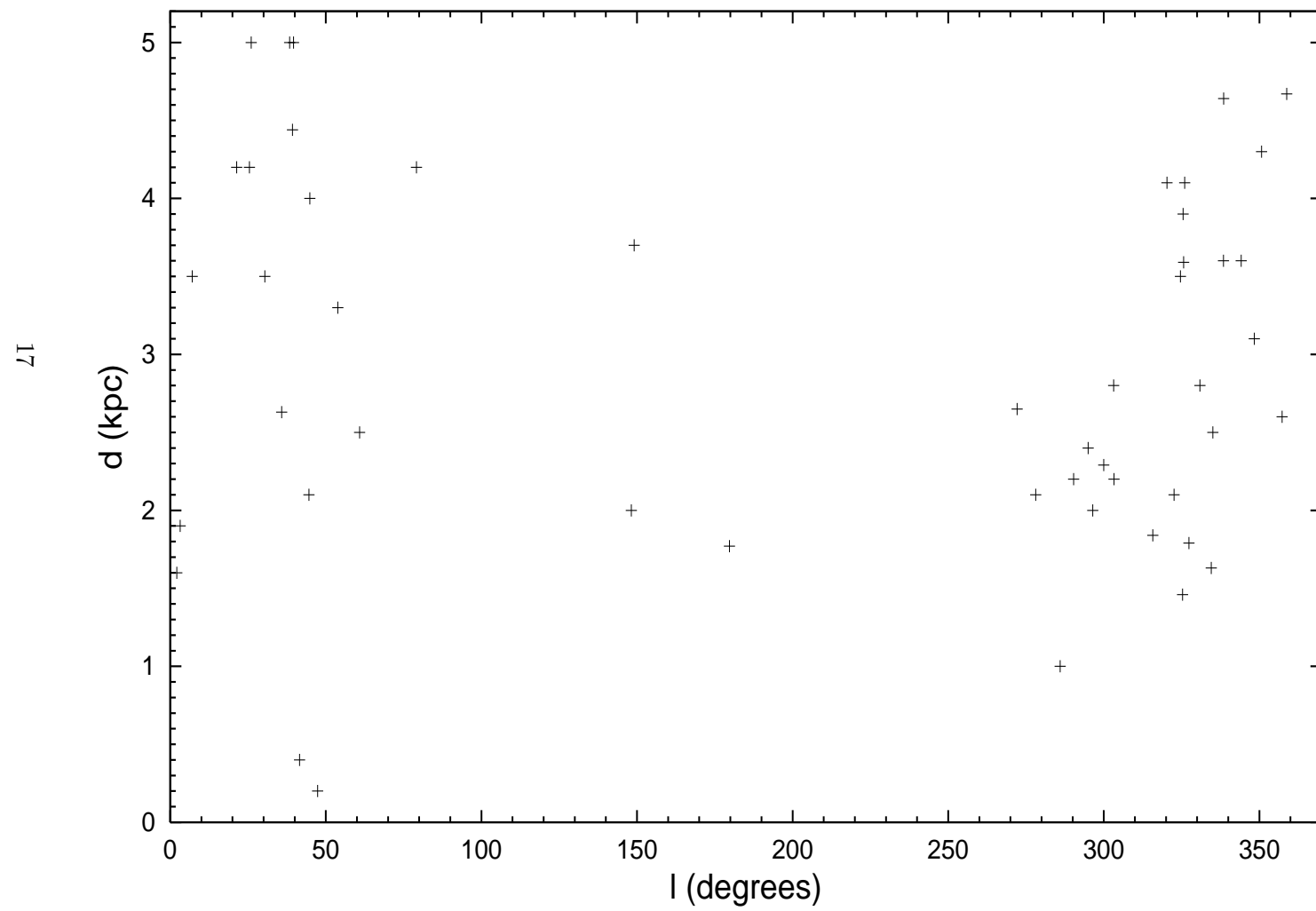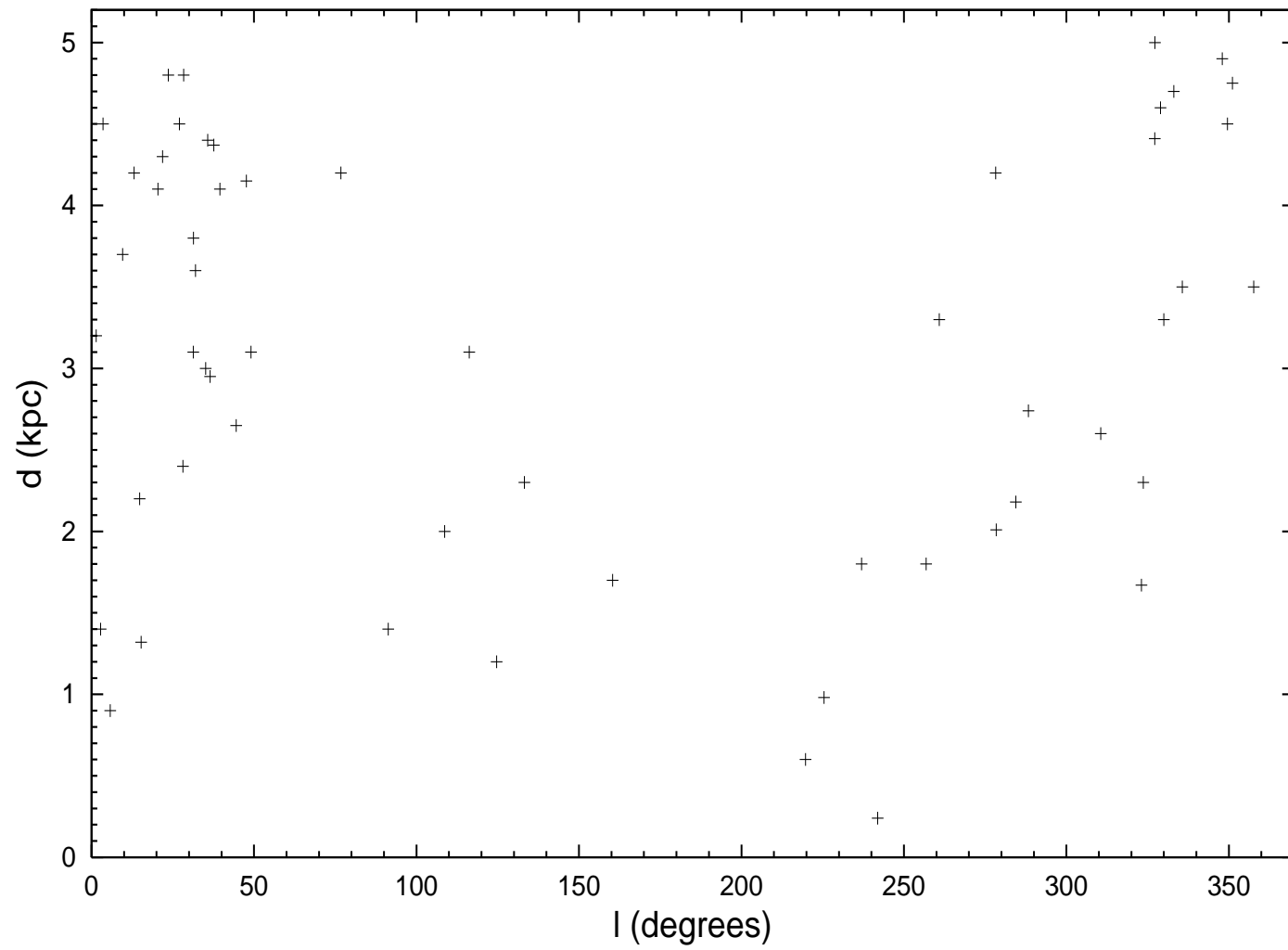**Figure 5b**: The luminosity at 1400 MHz L_{1400} versus l diagram for the pulsars with $0.6 < P < 1.3$ sec, $\dot{P} > 3 \times 10^{-15}$ s/s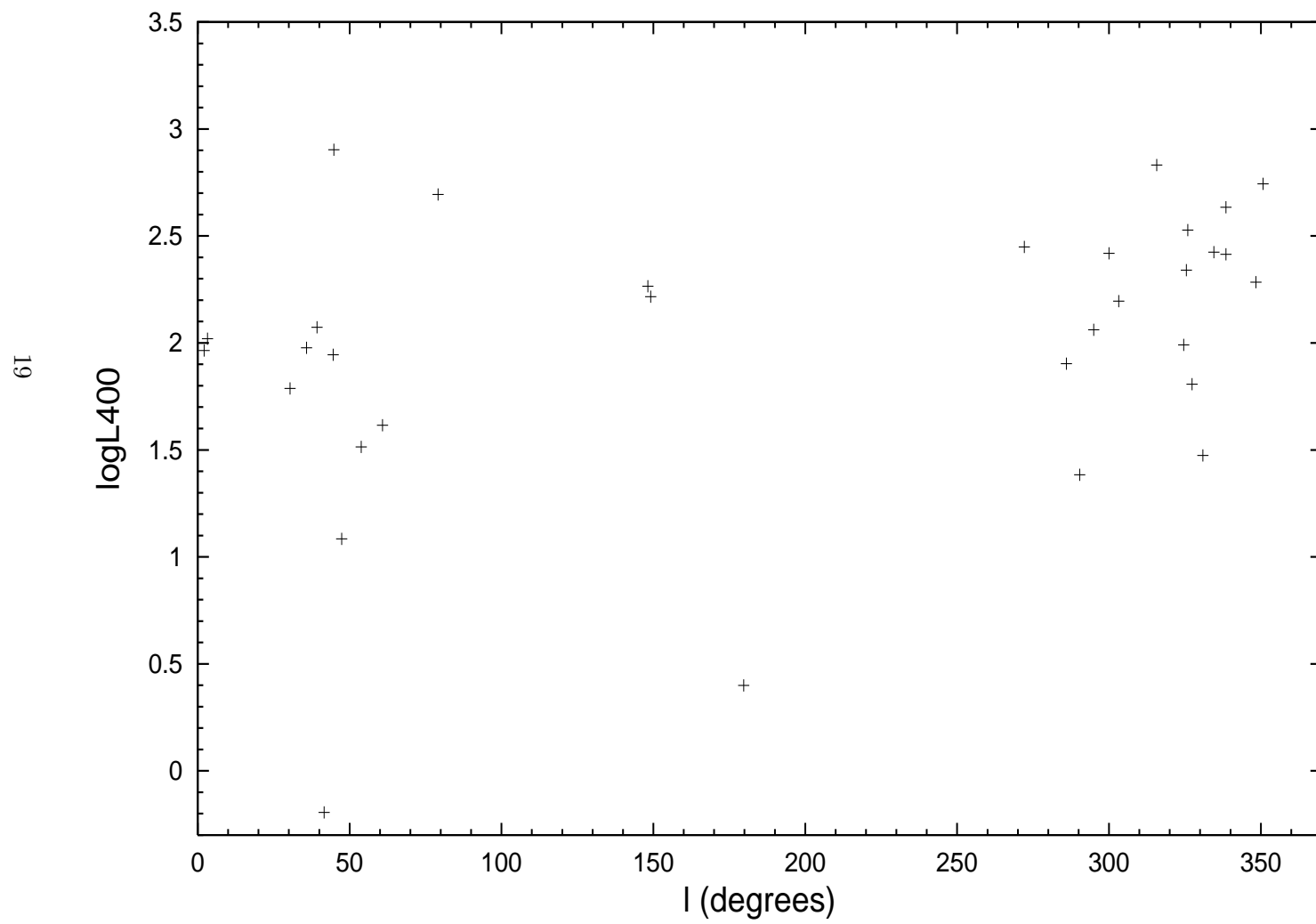,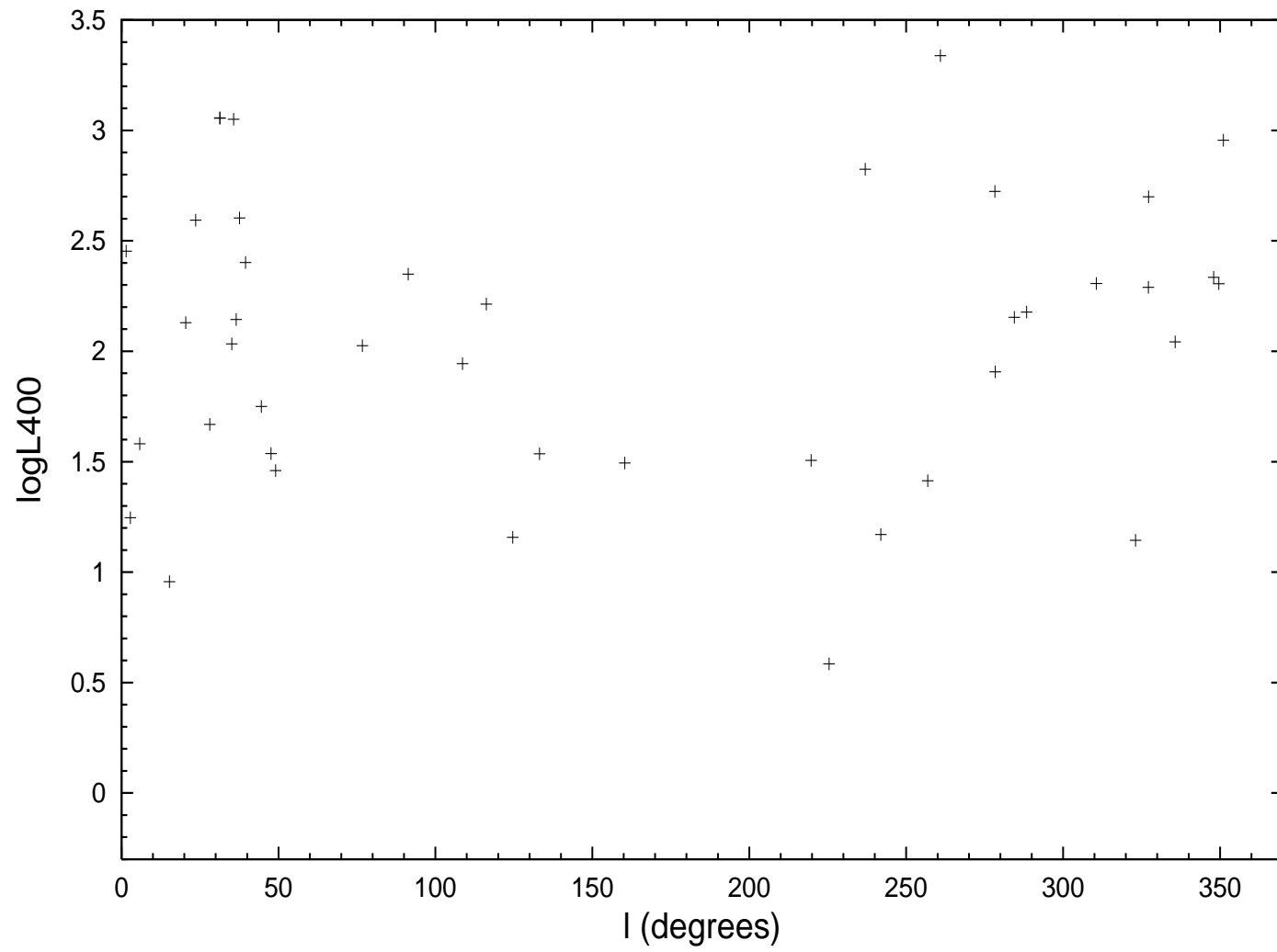 $6 \times 10^5 < \tau < 10^7$ yr and $d \leq 5$ kpc.